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Comparison of the performance of different converters for neutron radiography and tomography using fission neutrons

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ABSTRACT

An extensive study of the characteristic parameters of different types of converters for the detection of fast neutrons in radiography and tomography was performed. pp-Converters, plastic scintillators and some new scintillators were available for comparison. The investigated parameters were linearity, relative luminescent sensitivity, *signal-to-noise* ratio, spatial resolution and gamma-to-neutron sensitivity. A summary of the results and discussion are given.

1. Introduction

In recent years, neutron radiography and tomography using fast neutrons with energies higher than 1 MeV have become more and more popular. It can be widely used in many fields of application like industry, material science, etc. However, its efficient application at research reactors or accelerator facilities often lacks suitable converters to efficiently convert fast neutrons into directly detectable secondary radiation.

Therefore, the converter has become one of the most important parts of a fast-neutron detection system. An optimized detection system should have high efficiency for the conversion process. This is often in conjunction with the requirement of high spatial resolution. Furthermore, the sensitivity for gamma-rays of the converter should be low as in typical sources fast neutrons are often accompanied by a high gamma-ray background.

In the past, some results were published on the characteristics of the converters for detecting fast neutrons in radiography and tomography. Based on CCD imaging system, Rahmanian and Watterson [1,2] investigated the light output and spatial resolution of ZnS scintillators in accelerator-based fast-neutron radiography. Matsubayashi et al. [3] published the results on wavelength-shifting scintillators. de Haana and van der Hagen [4] gave the results on optimization of fast-neutron detection efficiency and spatial resolution. Bogolubov et al. [5] compared the spatial resolution of a thick luminescent polystyrene screen and a luminescent fiber optical screen. There are also results about fast-neutron converters with other imaging systems [6,7] and on other uses [8,9].

In this paper, series of different types of converters, like pp-converters, plastic scintillators, converters made of ZnS in a silica polymer (1:1) [10] and Gd_2O_2S:Tb+pp [11], etc. are compared on their characteristic parameters like linearity, relative luminescent sensitivity, *signal-to-noise* ratio, spatial resolution and gamma-to-neutron sensitivity using the CCD-based imaging system at the NEutron Computered Tomography And Radiography (NECTAR) facility of the Forschungsneutronenquelle Heinz Maier-Leibnitz (FRM II) at the Technische Universität München (TUM), Germany [12]. The comparison and discussion about the results will be given.

2. Experimental

The detection system of the NECTAR facility is based on a converter screen in combination with a thermoelectric cooled CCD camera (ANDOR DV434-BV, max. detection area $30\,cm \times 30\,cm$, working temperature $-50\,^{\circ}C$). The fission neutron flux at the detector position is about $1.0 \times 10^7\,cm^{-2}\,s^{-1}$ and the mean energy is about 1.9 MeV. More information on the facility and the fission neutron source are in [12].

In total, 16 converters were available for investigations (Table 1). They can be separated into two main groups: the so-called pp-converters (#1, #2) and the plastic scintillators (#4, #8–13). For reference, converters sensitive to thermal neutrons (#3), gamma-rays (#6) and X-rays (#7) were investigated, too.

The response of an optimum detection system shows a linear relation between the neutron fluence and the measured intensity for a preferably large range of fluence. In its experimental determination only the converters were exchanged, while the

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Table 1
Results of the character parameters of different types of converters for fast neutron radiography and tomography.

No.	Type	Size in (mm)	linearity slope B	FWHM (mm)	MTF at 10% (lp/mm)	γ/n (%)	S/N (dB)	Relative sensitivity
1	Fast neutron luminescence (pp:ZnS = 1:1)	200 × 300 × 2	4.66E−07	0.90	0.9	20	36.5	1.0
2	Fast neutron scintillation (30%ZnS in pp-matrix)							
	300 × 300 × 2.4		1.35	0.6	21	38.9	2.1	
		9.74E−07						
3	Thermal neutron screen (Li-6, LEV-20-00183)							
	300 × 300 × 0.4		0.67	0.8	25	35.1	0.7	
		3.22E−07						
4	Plastic scintillator (PKU)	Ø = 125, t = 3.8	1.09E−07	1.15	0.8		28.6	0.2
5	Luminescence (ZnS:silica polymer = 1:1, PKU)	110 × 100 × 2	2.53E−07	1.12	0.6	30	33.8	0.5
6	Co-60 gamma-sensitive (LEV-20-00185)	300 × 300, foil	9.93E−08			35	29.2	0.2
7	X-ray green sensitivity film FG-8 (Fuji)	240 × 300, foil	3.94E−07			55	36.2	0.8
8	Plastic scintillator (PTB)	200 × 200 × 3	1.07E−07	1.31	0.8	14	29.0	0.2
9	Plastic scintillator (PTB)	200 × 200 × 10	3.69E−07	1.40	0.7	14	34.1	0.8
10	Plastic scintillator (PTB)	200 × 200 × 20	7.57E−07	1.77	0.5	12	35.2	1.6
11	Plastic scintillator 8+9	200 × 200 × 13	5.13E−07	1.70	0.6	12	33.2	1.1
12	BC-412 (PSI)	300 × 300 × 3	1.02E−07	1.06	0.8	28	29.8	0.2
13	BC-416 (PSI)	140 × 115 × 2	7.10E−08	1.20	0.7	14	28.4	0.2
14	Gd_2O_2S:Tb+pp (8% Vol., VNIIA)	Ø = 35, t = 2	6.67E−07	1.63	0.4		33.2	1.4
15	Gd_2O_2S:Tb+pp (16% Vol., VNIIA)	Ø = 35, t = 2	9.74E−07	1.30	0.6		33.7	2.0
16	Gd_2O_2S:Tb+pp (24% Vol., VNIIA)	Ø = 35, t = 2	1.19E−06	1.25	0.6		34.6	2.4
17	Gd_2O_2S:Tb+pp (30% Vol., VNIIA)	Ø = 35, t = 1	9.06E−07	1.02	0.7		36.5	2.1

rest of the experimental conditions remained unchanged. The measuring times for all converters were varied from 0.1 s up to several hours. All images first were corrected for white spots [13] (the applied procedure does not change any characteristics of the converters) and then corrected for dark current. Selecting the same area in all images (300 pixels × 250 pixels), the corresponding mean gray values were determined as a function of the neutron fluence.

Based on the measurements for the linearity, the relative luminescent sensitivity was determined. As reference, the pp-converter (#1) was selected, which has an absolute detection efficiency of about 0.5% [14].

The determination of the *signal-to-noise* ratio, defined by

$$\frac{S}{N} = 20\ \log\left(\frac{\text{mean}}{\text{std dev}}\right) \tag{1}$$

was based on the measured data for linearity, but a smaller image area of only 40 pixels × 30 pixels in the centre of the beam was selected for determination of the mean value and its standard deviation in order to reduce the influence of non-homogeneities of the neutron beam and converters.

For the measurements of the spatial resolution, an iron slab was positioned in the centre of the turntable of the sample manipulator, with one side parallel to the neutron beam direction. By a series of measurements at slightly varying angular positions (0°, ±0.3°, ±0.5°, ±0.7°, ±1°) and only accepting the result for the best spatial resolution for each type of converter, possible angular displacements were eliminated. These data were evaluated applying two different procedures. First, the edge-spread function (ESF) was used to calculate the full-width-at-half-maximum (FWHM) (Fig. 1):

$$\varphi(x) = a\left\{\frac{1}{2} + \frac{1}{\pi}\tan^{-1}[\lambda(x - x_0)]\right\} + b \tag{2}$$

with $\varphi(x)$ the mean gray value, x the pixel number, x_0 the edge position as pixel number, λ the resolution parameter (FWHM = $2/\lambda$), and a and b constants.

The second evaluation is based on the calculation of the modular transfer function (MTF) derived from the line-spread function (LSF) by Fourier transformation. The spatial resolution was defined as the MTF value at 10%.

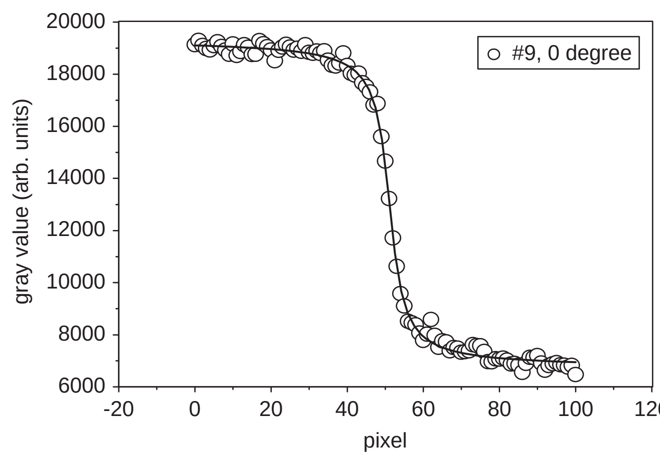

Fig. 1. Sample to explain the mathematics process with edge–spread function, converter #9, angle of the turntable = 0°.

At the measuring position of the NECTAR facility a mixed neutron and gamma-ray field is present. To estimate the gamma-to-neutron sensitivity of the different converters, measurements using a lead step wedge with thicknesses ranging from 5 to 100 mm were performed. All radiographs were calculated from sets of 5 images with object, 5 open-beam images and 5 dark images, each, after white spot correction [13]. The measurement time per image was 60 s. As the gamma spectrum at the measuring position is not yet known, the evaluations only gave rough estimates. Assuming that the measured signal is composed of transmitted neutrons, transmitted gamma-rays and a scattering background, the function

$$y = Ae^{-\mu_n x} + Be^{-\mu_\gamma x} + C \tag{3}$$

which is based on the transmission law, was used to fit the curves of the mean gray values y as function of the thicknesses x of lead. A, B are the numbers of transmitted neutrons and gamma-rays, respectively, and C is the scattering background component. The gamma-to-neutron sensitivity is then defined by B/A.